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Geology and Geochemistry for Medium Enthalpy Geothermal System of Mount Pandan

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ABSTRACT

Geothermal field of Mount Pandan is located between Bojonegoro, Madiun, and Nganjuk. Based on the geological condition, Mount Pandan lies in the middle of Kendeng Basin and at the northern part of active volcanic. Mount Pandan is a non-active volcano, early Pleistocene in age with elevation 800 masl. This research conducted by petrographic and geochemistry analysis to identify the conceptual model and geothermal system of Mount Pandan. The lithology of the study area consists of volcanic breccia, andesite intrusion, carbonate siltstone, and limestone. Furthermore, there are 12 warm springs produced by the emergence of geothermal heated groundwater that rises to the surface that controlled by strike-slip fault. JR-1, JR-2, JR-3 and BK group are controlled by NE-SW sinistral fault and the other of manifestations in Mount Pandan are controlled by NW-SE dextral fault. JR-1, JR-2, and JR-3 warm springs emerge in 206 masl as chloride water and JR-4, JR-5, BK group, TD-1 and PG-1 warm springs emerge in 490 masl as bicarbonate water. Based on the geochemistry analysis, the reservoir temperature of Mount Pandan is 185°C, which implies that this mountain has geothermal medium enthalpy system. In addition, the reservoir rocks are carbonate sedimentary rocks from Kalibeng Formation that its heat source associated by magmatic activities.

1. INTRODUCTION

Mount Pandan is located in Java Island, about 688 km SE from Jakarta. Mount Pandan is one of an extraordinary stratovolcano in Java Island. Java is divided into four zone base on the stratigraphy and tectonic aspects, there are Southern Mountain Zone, present-day Volcanic Arc, Kendeng Zone, and Rembang Zone (Smyth, et al, 2005). It located in the middle of Kendeng Basin and in the north of Quartenary and recent volcano in Java Island (Figure 1). Agastya et al. (2017) interpreted that the presence of the Mount Pandan at the same time with the process of folding and uplifting of Kendeng Basin. Hussein (2016) expected the Kendeng Basin began to uplift at the beginning of the Klitik limestone deposition, in early Pliocene. The Ministry of Energy and Mineral Resource (MEMR) (2012; 2017) expected geothermal power capacity of Mount Pandan amounts to 60 MW and the plan of development (POD) is 40 MW.

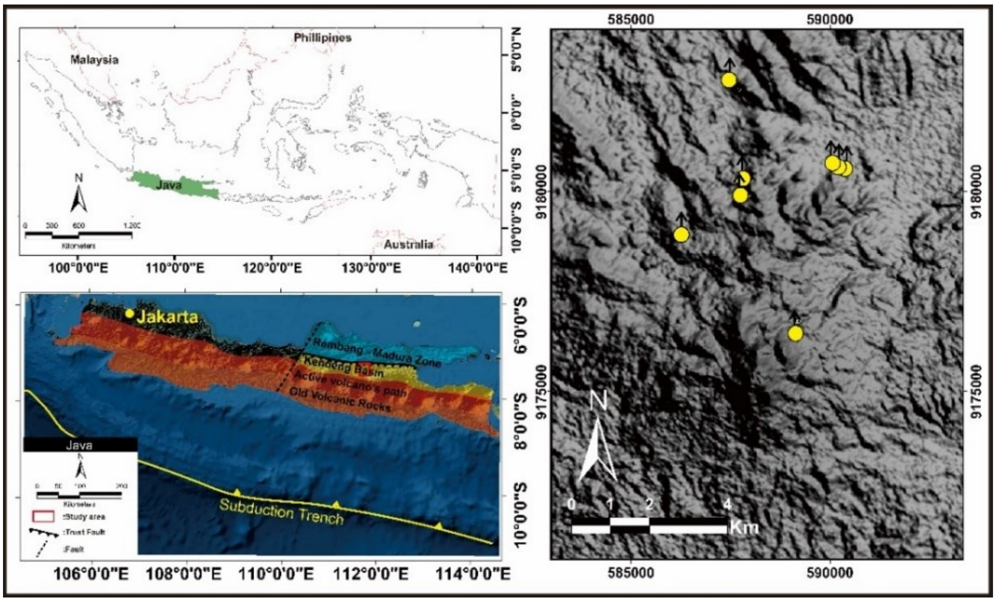

Figure 1: Study Location Map. Lineation of fault system resulted in local stress and volcanism at Mount Pandan field.

The geothermal resource in Mount Pandan is indicated by the presence of manifestations consisting of warm springs which associated with the late Neogene fault along quartenary volcanic in the middle of Kendeng Basin (Figure 1). In this paper, data that are used are a combination of surface observation data. This research was assisted by using structural analyses, chemical analyses, and petrography thin section by using a polarization microscope. The water chemistry data has obtained from Pusat Sumber Daya

Geologi (PSDG, 2013) to support in building the geothermal conceptual model of Mount Pandan. There are 12 manifestation data of Mount Pandan that are found in Jari, Pragelan, Tadahan, and Banyukuning. This information is used to better constrain which associated with surface manifestation. The geological framework includes the distribution of lithology and structural environment, a geothermal fluid movement which integrated into conceptual models for the Mount Pandan geothermal system.

2. GEOLOGY SETTING

2.1 Stratigraphy

The stratigraphy of Mount Pandan can be simplified into Neogene sediments overlain by Quartenary volcanic, volcaniclastic and Recent sediments (Figure 2). Pringgoprawiro and Sukido (1992) explain that Neogene Sedimentary rock consisting of Kerek Formation (Tmk), Kalibeng Formation (Tmpk), Klitik Formation (Tpk), and Sonde Formation (Tpso). Kerek Formation consists of marl, sandstone, claystone, and limestone. Kalibeng Formation consists of Globigerina massive marl, greenish and silty marl. At the upper of Kalibeng Formation, there is interfingering of Atas Angin Member characterized by volcanic sandstone, tuff, conglomerate, and breccia. Klitik Formation consists of limestone, marl, and clay. Sonde Formation consists of intercalation between claystone and volcanic sandstone as an end of marine depositional series in the Upper Pliocene. The sedimentary rocks uplifted, folded, faulted and locally metamorphosed by Quartenary Andesite Intrusion. Pringgoprawiro and Sukido (1992) explain that Mt. Pandan Formation consists of Pleistocene Andesite Breccia (Qpv) and Pleistocene Andesite Intrusions. Kabuh consists of conglomerate, sandstone and locally marl and clay intercalations. Notopuro consists of tuff, tuffaceous sandstone, and conglomerate.

Thoha et al. (2014) divided stratigraphy of Mount Pandan northern slope into four volcanic rock units. The oldest to the youngest volcanic rocks are Mount Nangka unit, Mount Telogo Gebang unit, Mount Lawang unit and Mount Pandan unit. The volcanism is moved to the north and ends in the south part of the area in the Pleistocene. Mount Pandan is located in the south part of the study area, which the morphology still shows the volcanic cone landform. The youngest volcanic rock is predicted to become the heat source of the geothermal system in this study area.

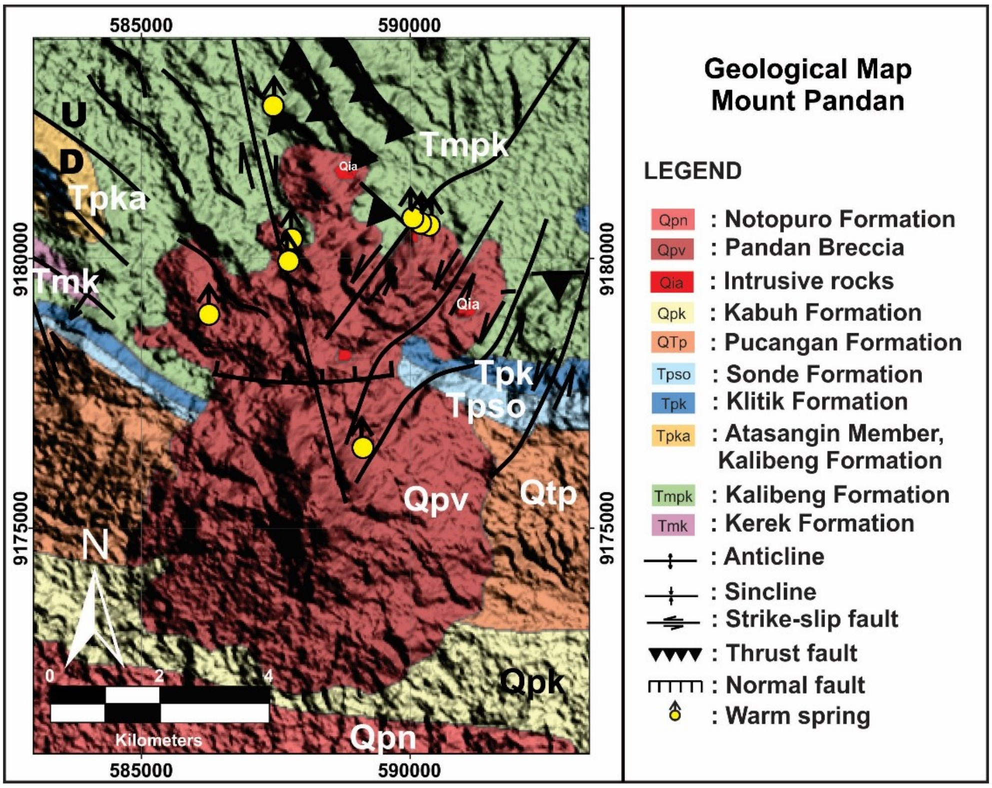

Figure 2: Geological map of Mount Pandan (modified from Pringgoprawiro and Sukido, 1992). Thermal manifestations in Pandan discharge along with the main strike-slip fault system.

2.2 Rock Characteristic

Rock characteristic of Mount Pandan identified by surface outcrop observation and supported by petrography analyses using polarization microscope. In carbonates, samples are used alizarin red ash to differ the dolomite and calcite. The petrography analyses can be seen in Figure 3.

The Kerek Limestone lithofacies consists of massive gray limestone. Based on the composition, the presence of algae fragment, organic clasts which almost changed into calcite, and carbonates cement like micrite and microspar indicate significant reworking of carbonate rocks. High intraclast porosity showed that this lithofacies is highly dissolved (Figure 3a).

The Kalibeng Globigerina Massive Marl lithofacies consists of gray carbonate siltstone and claystone (Figure 3d). Massive and parallel lamination is the dominant sedimentary structure. However, cross-bedding and convolute is also common. Based on the composition, the presence of foraminifera especially Globigerina, organic clasts, and carbonates cement indicate significant reworking of carbonate rocks. This lithofacies is spread widely in the study area.

The Pandan Volcanic Breccia lithofacies is composed of angular to subangular fragments in a brown, grey, and black of coarse sand to pebble. The outcrop is mainly weathered and fractured. They occur widely in the study area. The fragment size usually is in the range of pebbles and cobbles with andesite fragment. The matrix of the deposits is commonly composed of lithic and tuff (Figure 3b).

The Pandan Andesite intrusion which identified in the study area classified as an intermediate and shallow intrusion. The texture is hypocrystalline. Intermediate plagioclase is the most abundant phase with subordinate hornblende, clinopyroxene, amphibole, and quartz. The distribution of this andesite is localized in a narrow area around 300-700m. Andesite characteristic can be seen in Figure 3c.

The layer below of Mount Pandan are marine sedimentary rocks, and the volcanic rocks have e thin thickness, so can be predicted that the reservoir of Mount Pandan is these sedimentary rocks.

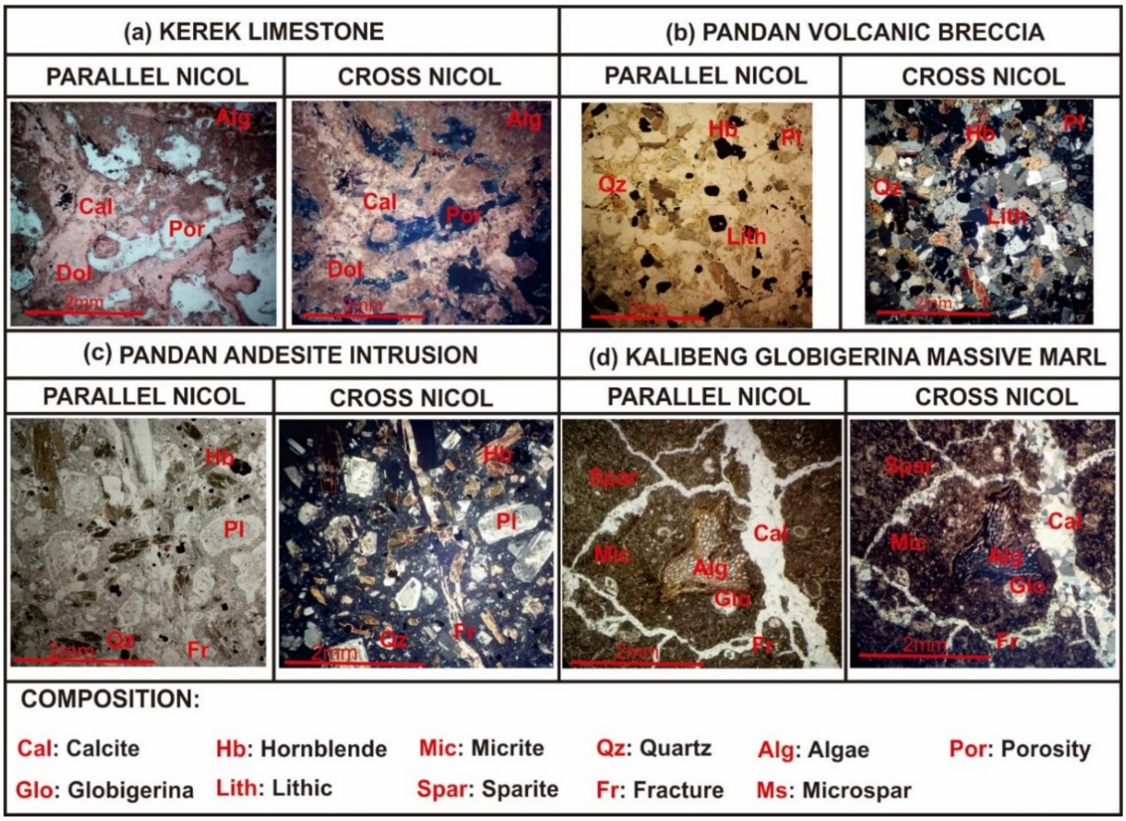

Figure 3: Mount Pandan rock characteristic. The top image is the outcrop and the bottom image is a thin section analyzed with a polarized microscope in parallel and cross nicol.

2.3 Geological Structure

Prasetyady (2007) (as cited in Thoha et al., 2014) explained that the major geological structure in Mount Pandan is NE-SW Faults and NW-SE Fault interpreted as reactivated Kendeng (Upper Miocene-Lower Pliocene) faults forming fault corridor, triggering the appearance Mount Pandan (Lower Pleistocene). Beside the strike-slip fault, there is E-W thrust fault (Figure 4), the older geological structure that formed by regional contraction from subduction product in the south Java Island.

The E-W trust fault indicates that it was formed during Middle Pleistocene during Kendeng Basin uplifting and folding. It formed by regional contraction from subduction product in the south Java Island. Thermal manifestations are also localized along NE-SW main fault and fractures, supporting this interpretation (Figure 2). The NE-SW and NW-SE fault trend is interpreted to be synthetic fault from N-S contraction. The NE-SW and NW-SE fault trend is interpreted to be synthetic fault from N-S local contraction during Pleistocene. And there is E-W normal fault that interpreted as the youngest fault in this area that formed in the last phase (Figure 2).

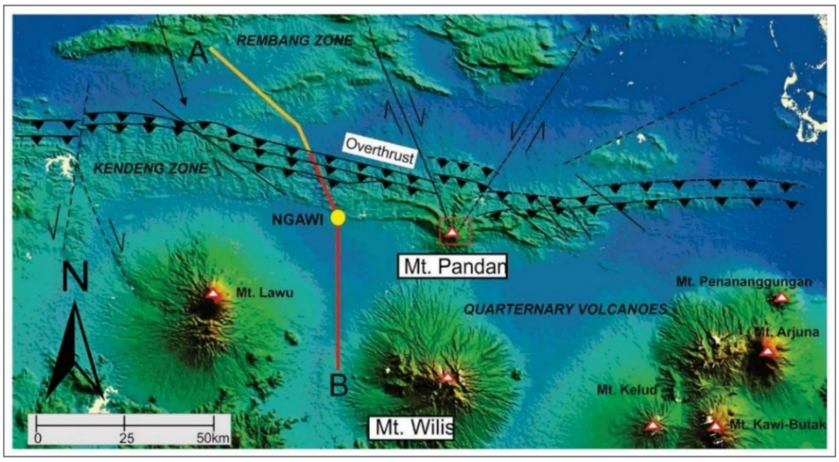

Figure 4: NE-SW and NW-SE strike-slip faults and thrust fault in Mount Pandan and surrounding area (Prasetyadi as cited in Thoha et al., 2014).

2.4 Volcanostratigraphy

Volcanostratigraphy units are determined based on the eruption center, ridge lineaments, stream or drainage system, and also base of volcano boundaries (Asokawaty, 2017). The topographic map analysis scale is 1:50,000. The volcanostratigraphy units consist of Pandan Crown and Nangka Crown. The Nangka crown, located in the northern study area is identified as the oldest unit and followed by Pandan crown as the youngest located in the south of Nangka Crown. In Nangka Crown, there are four hummocks i.e. Pragelan, Krondonan, Gondang, and Jari. The Pandan Crown consists of three hummocks i.e. Rejoso, Klangon, and Klino (Figure 5). The delineation of volcanostratigraphy have the same correlation with the distribution of volcanic rocks unit (Qpv), so the distribution of Qpv is controlled by the morphology of Mount Pandan. There are two crowns, The Pandan crown was once an active volcano that shown from the radial pattern of eroded ridge and drainage pattern but now is in a dormant condition. While the Nangka crown which is older than Pandan crown didn't have the radial pattern because of the eroded and weathering process. The manifestations emerge in Pandan and Nangka crown, which indicate there is volcanic activity below the study area that could be a heat source.

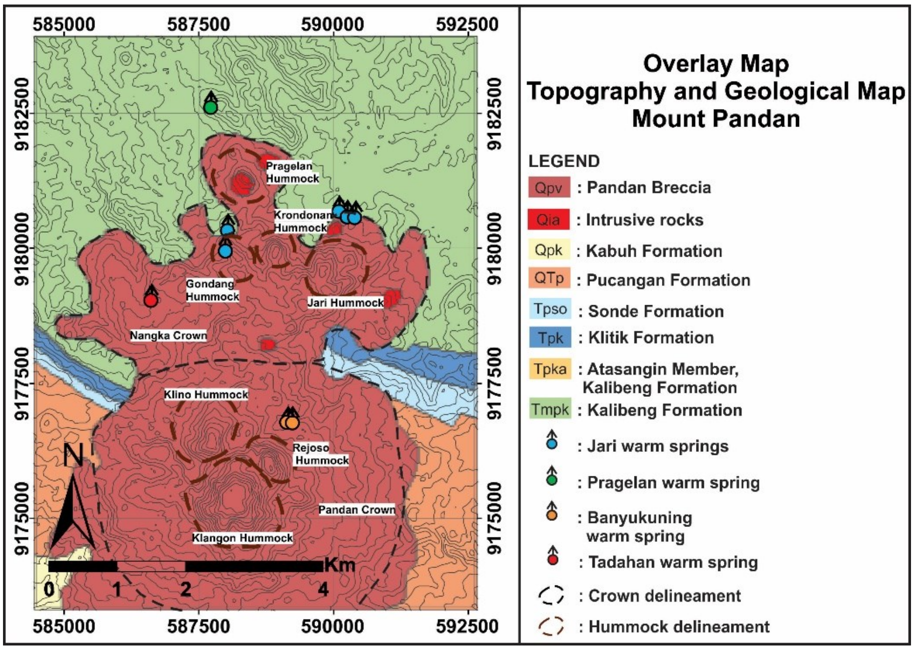

Figure 5: Distribution of volcanostratigraphy units on the overlayed of topography and geological maps of Mount Pandan

3. GEOTHERMAL EXPLORATION

3.1 Geothermal Manifestations

Based on field observations, there are two groups of geothermal manifestations which classified as warm springs. There are Banyukuning and Jari warm springs (Figure 6). Banyukuning (BK) warm springs group (Figure 7a) is located in Jomblangjati, and the warm springs emerge in the near of river from breccia rocks. There are three warm springs with radius of 300 meters. There are yellow iron oxide deposits in each spring with warm slightly yellow water and strong sulfuric odor. Gas bubbles emerge from the spring. The temperature of the water is 36.7ºC, while the air temperature is 32ºC.

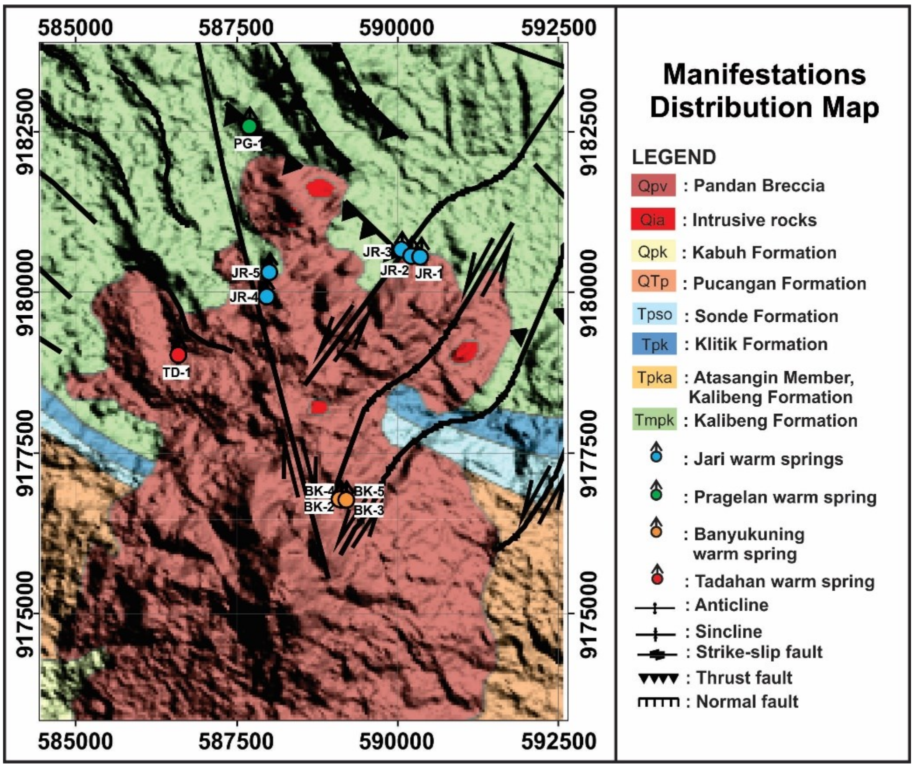

Figure 6: Distribution of geothermal manifestation in Mount Pandan.

Jari warm (JR-1, JR-2 and JR-3) springs group (Figure 7b) are located in Jari Village, with warm springs of 200 meters radius. Lithology in this area was andesite lava. Travertine (carbonate sinter) and alteration were found (Figure 6b.2). Generally, Jari springs are warm but one manifestation classified as cold spring because it mixed with the fluvial system. Local residents built a pond to collect the warm water from the spring. The temperature of warm water is 43.1ºC and the air temperature is 32ºC.

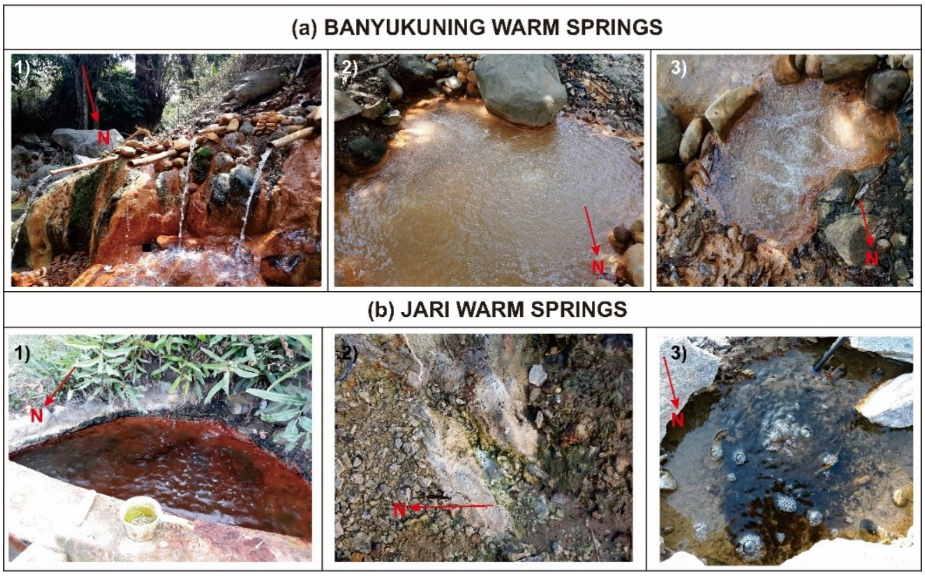

Figure 7: (a) Banyukuning warm springs group, (b) Jari warm springs group.

3.2 Geochemistry of Manifestations

Based on the geochemistry data from PSDMBP in 2013, there are four groups of geothermal manifestations. They are located in Jari, Pragelan, Tadahan, and Banyukuning. The result of ion balanced analysis, known that all manifestation have ion balanced <5% which means all water sample of manifestations have good quality and proper to conduct interpretation based on this data (Table 1).

Table 1: Results of ion equilibrium analysis at Mount Pandan geothermal field

Code		JR-1	JR-2	JR-3	JR-4	JR-5	PG-1	BK-1	BK-2	BK-3	BK-4	BK-5	TD-1
Elevation	(m)	206.58	207.21	212	314.83	300.73	259.36	486.02	491.13	490.23	490.28	490.23	337.2
Temperature	(˚C)	40	35.4	43.1	32.3	32.8	32.6	35.5	36.7	33.1	28.2	32.3	33.2
pH		6.21	6.39	6.39	6.43	6.11	6.82	6.28	6.57	6.35	5.92	7.47	6.41
Li	(mg/L)	6.09	7.36	9.77	-	0.31	0.02	1.47	1.3	1.01	0.15	0.98	0.41
Na		1697	1598	4215	23	99	27	372	324	254	54	227	296
K		94	108	247	2	17	7	33	29	21	5	22	18
Ca		142.3	69.1	32.9	63.7	172.4	147.4	196.5	212.7	115.6	66.1	91.3	70.2
Mg		19.73	25.41	34.78	11.70	63.98	37.00	78.90	83.43	54.22	26.10	52.35	41.10
SiO2		117	134	163	110	159	109	177	170	163	148	160	151
B		38.01	54.53	128.52	0.20	0.58	0.00	9.18	8.52	5.66	0.47	5.55	4.38
Cl		1871	1970	5208	12	18	8	717	564	393	48	393	393
F		1.0	0.5	-	0.4	0.6	1.2	0.5	0.8	0.9	0.9	1.2	0.2
SO4		237	148	249	2	-	280	39	36	10	40	49	2
HCO3		1334	1172	2077	277	1035	327	685	882	609	330	401	542
NH4		3.0	28.0	63.5	0.1	1.6	0.2	3.9	3.1	2.4	0.4	1.3	3.4
Fe		0.02	0.01	0.01	0.02	0.02	0.02	-	-	0.01	0.01	0.01	0.01
Charge Balance		4%	2%	3%	3%	3%	1%	2%	2%	2%	2%	2%	1%

3.2.1 Cl-HCO$_3$-SO$_4$ Diagram

Based on the ternary diagram plotting of the major anions Cl^-, HCO_3^- and SO_4^{2-} as seen in Figure 8a, there are three types of water, chloride water, chloride-bicarbonate water, and bicarbonate water. JR-1, JR-2, and JR-3 are identified as chloride water, JR-4, JR-5, BK-4, and PG-1 are bicarbonate water and the rest are chloride-bicarbonate water.

JR-1, JR-2, and JR-3 warm springs showed a high concentration of Cl- which includes chloride water. A high Cl concentration can indicate water reservoir (Nicholson, 1993). Additionally, there is a higher HCO_3^- concentration compared to other manifestation, which means that mixing occurs. HCO3 enrichment explains that reservoir water experiences mixing with rainwater. This manifestation is deep geothermal fluid that comes directly from the reservoir and indicates areas that have high permeability (Nicholson, 1993).

JR-4, JR-5, BK-4, and PG-1 warm springs composed of bicarbonate water which located in peripheral - surface water zone with a dominant concentration of HCO_3^-. These warm springs are the product of steam and gas condensation into poorly-oxygenated sub-surface groundwaters.

Banyukuning (BK-1, BK-2, BK-3, and BK-5) and Tadahan are chloride-bicarbonate waters. They are formed by the dilution of chloride fluid by either groundwater or bicarbonate water during lateral flow. These warm springs are not classified as reservoir water but they were the product of near-surface mechanism due to the mixing of the reservoir water with groundwater or surface water. The emergence of these springs can indicate the margins of major upflow zone and outflow zone.

3.2.2 Na-K-Mg Diagram

Na-K-Mg diagram (Figure 8b) presents the equilibrium condition of the geothermal fluids. Based on the Na-K-Mg diagram, there are three warm springs which are plotted on partial equilibrium zone, i.e. JR-1, JR-2, and JR-3. This shows that the manifestation has undergone dilution. This fluid manifestation comes from a reservoir that has been interacting with meteoric water but this fluid still shows the reservoir fluid properties. This is because the dilution concentration is still low, which indicates that the fluid reacted with wallrock, but the wall rocks have a big pathway through and good permeability so it can show reservoir fluid. By doing so, these water samples representative to calculate the reservoir temperature. Based on Na-K geothermometer, Mount Pandan has a reservoir temperature of 185°C (Figure 8b) and according to Hochstein (2000), it is classified as a medium enthalpy geothermal system.

Banyukuning warm spring showed a high concentration of Mg and plotted as immature water. Immature water zone and near $\sqrt{Mg}$ peak point showed that there was a high influence of groundwater in the systems. This is in accordance with Cl^-, HCO_3^- and SO_4^{2-} a plotting diagram that proved the interaction with groundwater or surface.

3.2.3 Cl-Li-B Diagram

Conservative elements analysis from Cl-Li-B diagram (Figure 8c) gives the information about the process that occurs in sub-surface when the fluid flow to the surface. Based on Cl-Li-B diagram, all samples except JR-5 are plotted in near of Cl peak because all manifestation have high chloride concentration than boron concentration. It means that warm springs in this study area undergo cooling process conductively when the fluid flows to the surface. JR-5 has trend with a high Li than other samples, which indicate this sample undergoes interaction with wall rocks (leaching rocks).

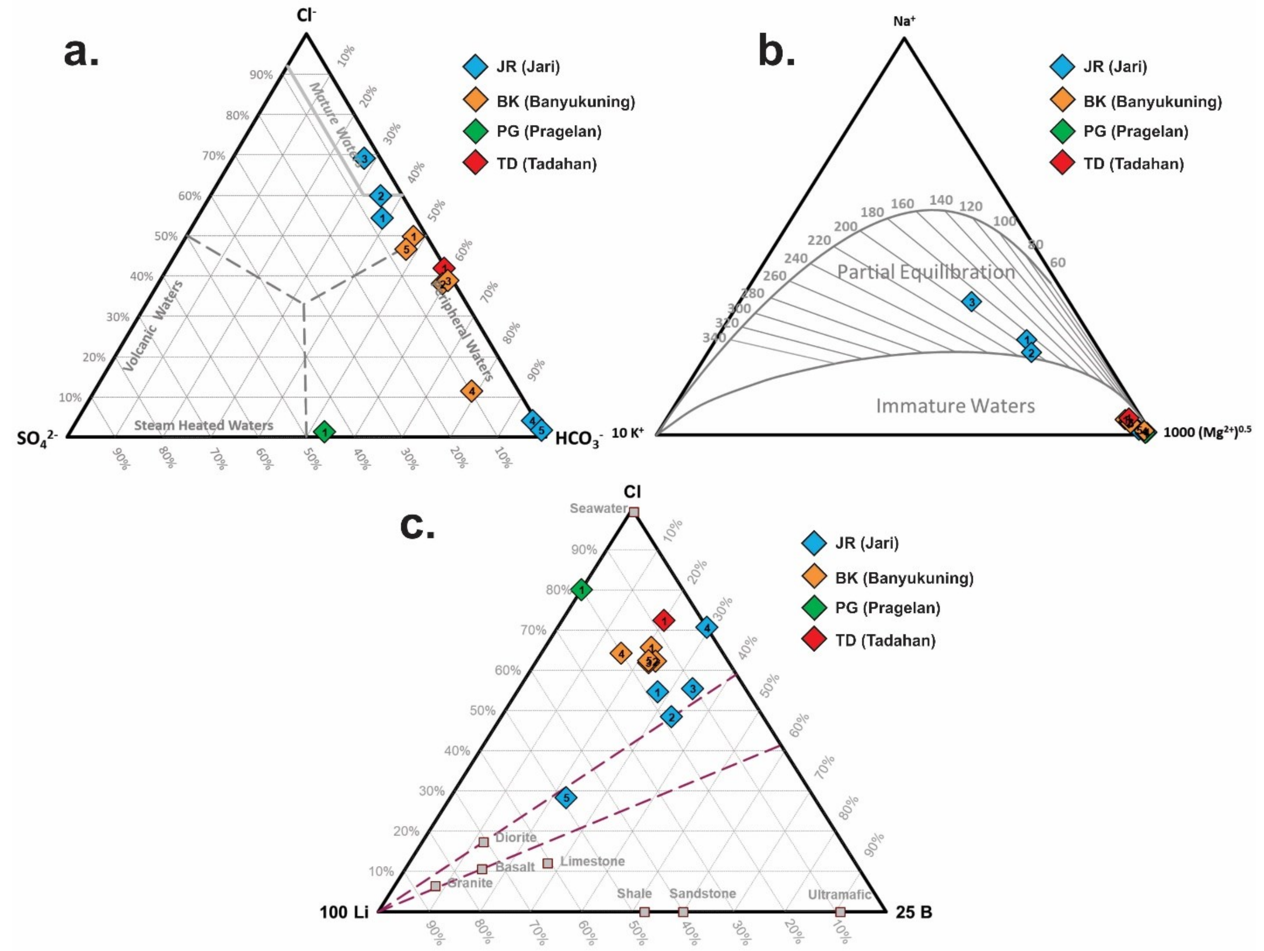

Figure 8: Chemical fluid plot of Mount Pandan manifestation. (a) Cl-HCO_3-SO_4 diagram plot for geothermal fluid type, (b) Na-K-Mg diagram for geothermal reservoir temperature, (c) Cl-Li-B diagram for the geothermal fluid environment.

Based on chemical data (Table 1), there is an abnormal value of elements calcium. The Ca value in Mount Pandan is relatively higher than other bicarbonate water and chloride water. In several geothermal fields in the world, bicarbonate water and chloride water generally have tens of mg/kg of the element of calcium (Nicholson, 1993). This is interpreted due to the rock condition in the study area, under the volcanic rocks, there is Kalibeng formation that consists of gray carbonate siltstone and claystone which is a marine sedimentary rock with organic carbonates materials.

Besides information obtained from Ca values, high B values (hundreds) indicate the presence of sedimentary rocks in the Mount Pandan geothermal system. This is in accordance with the geological conditions which under the volcanic rocks, there is Kerek formation, namely marine sedimentary rocks.

3.2.4 Geoindicator

According to Nicholson (1993), there are several parameters in determining the location of upflow zone that related to chemical elements of manifestation, namely geoindicator that have low values of the Na/K, Na/Ca, Mg/Ca and HCO_3/SO_4 ratio. This ratio is used to complete the analysis of the water type of manifestation in determining the zone of the geothermal system of the research area. The geoindicator calculation of each manifestation will group the manifestation based on its value of the ratio. Each manifestation has a value which guides to interpolate the value between the manifestations to create contour lines. By doing so, the upflow zone can be predicted. Nicholson explains that the higher Na/K and Na/Ca ratios are indicative of lateral flow, near-surface and conductive cooling and the lower ratios means that the fluid have reached the surface rapidly that associated with upflow zone and permeable zone (Figure 9a and Figure 9b), the higher Mg/Ca ratios can indicate near-surface reactions leaching Mg from the rock or dilution by groundwater that associated with the outflow zone (Figure 9c) and the higher HCO_3/SO_4 ratios in lateral flow (outflow zone) can be seen in Figure 9d.

Besides determining the upflow and outflow zone, geoindicator can give information about the fluid flow direction. Geothermal fluid circulates due to the buoyancy force of water that is hotter above the heat source so that the cooler water flow downward due to the impulse from the hotter water, it forms convection circulation. The fluid circulation is related to the geothermal system zonation, the fluid that flows directly to the surface is an upflow zone and the lateral flow of fluid toward the outflow zone.

Figure 9, shows that the upflow zone is located in the southern area from Banyukuning manifestation and consistently JR-1, JR-2, and JR-3 samples show that area is outflow zone which is marked in blue on the map and the fluid flow direction is from southern area to the north-eastern area (JR-1, JR-2, and JR-3) and the fluid flow from the reservoir can be seen in Figure 10.

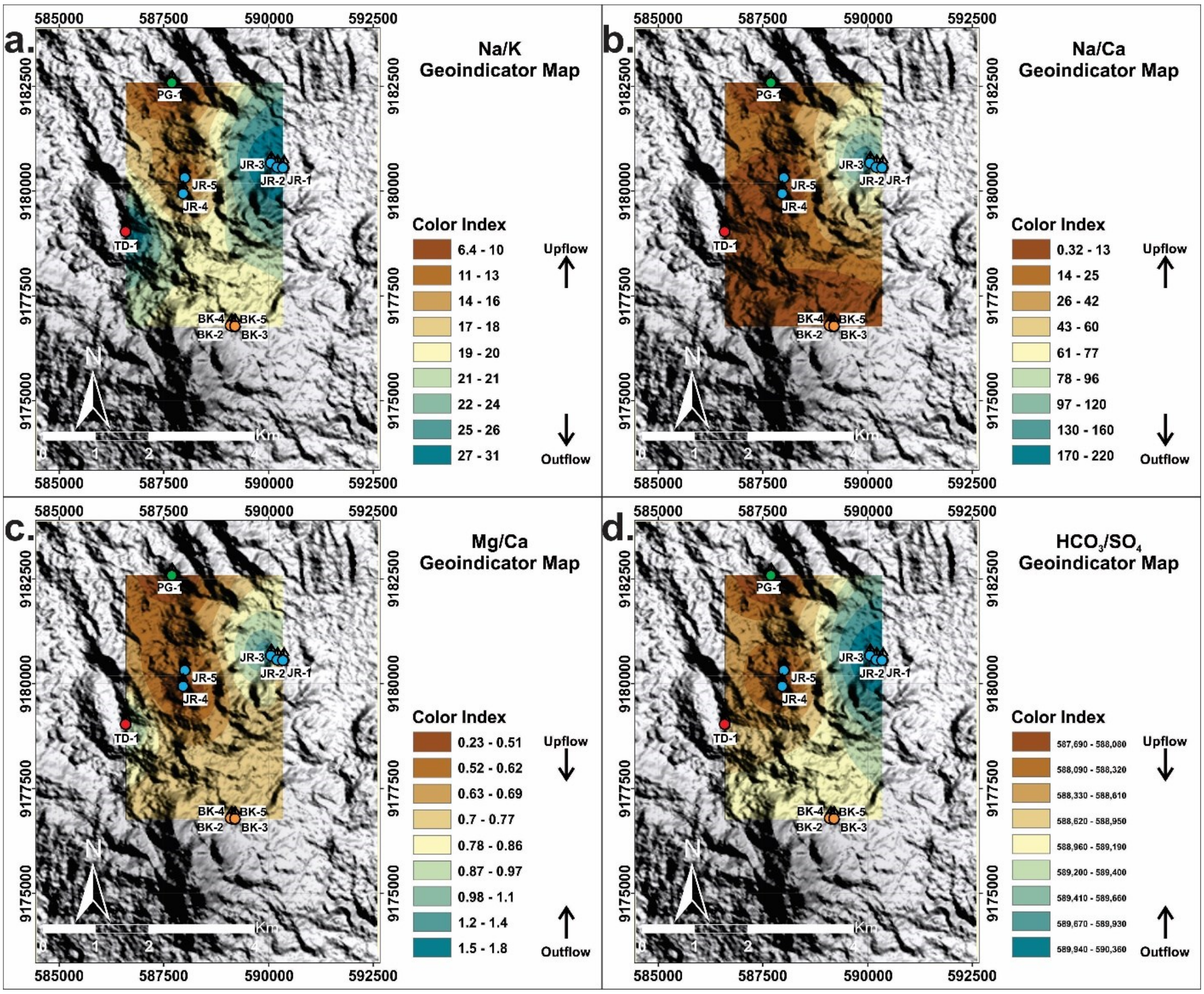

Figure 9: The geoindicator maps of ratio Na/K, Na/Ca, Mg/Ca and HCO_3/SO_4 ratio which show the upflow zone is in the southern area.

3.3 Geothermal System of Mount Pandan

According to the geological conditions and morphology, Mount Pandan is a volcanic-hydrothermal system with medium enthalpy. Based on the geochemical analysis of the manifestations that have been carried out it can be shown that the characteristic of 12 manifestations is classified as outflow zone discharge which in the margin area of the geothermal system. All the manifestation from the Jari, Tadahan, Pragelan and Banyukuning warm spring emerge along the fault on the surface that are controlled by thrust fault, dextral fault and sinistral fault. Heat source from this geothermal system is a magma chamber that controls the Early Pleistocene volcanic activity of Mount Pandan. The location of the magma chamber is thought to be under the upflow zone, as the upflow zone is a vertical fluid discharge zone that interpreted to be located on the southern area from Banyukuning manifestations group, based on chemistry and volcanism evolution.

Based on the geochemical analysis, the reservoir rocks in the Mount Pandan geothermal system are sedimentary rocks, that means have a correlation with the electromagnetic data (MEMR, 2017), the reservoir has >10-60 ohm meters. The cap zone in Mount Pandan geothermal system is the product of Pandan volcanic that already became altered volcanic rock (MEMR, 2017) which has impermeable properties that can maintain the heat. The fluid flow is controlled by fault, there are thrust fault, normal fault, strike-slip fault, but the main fault that control the emergence of manifestations are thrust fault and strike-slip fault. E-W thrust fault which cut off by NE-SW sinistral fault and NW-SE dextral fault that becomes fluid pathways to appear on the surface.

In order to understand the flow of fluid from the reservoir to the surface, a morphological profile is made which passes through the types of bicarbonate and chloride warm springs. The predicted fluid flow and the geothermal system can be seen in Figure 10.

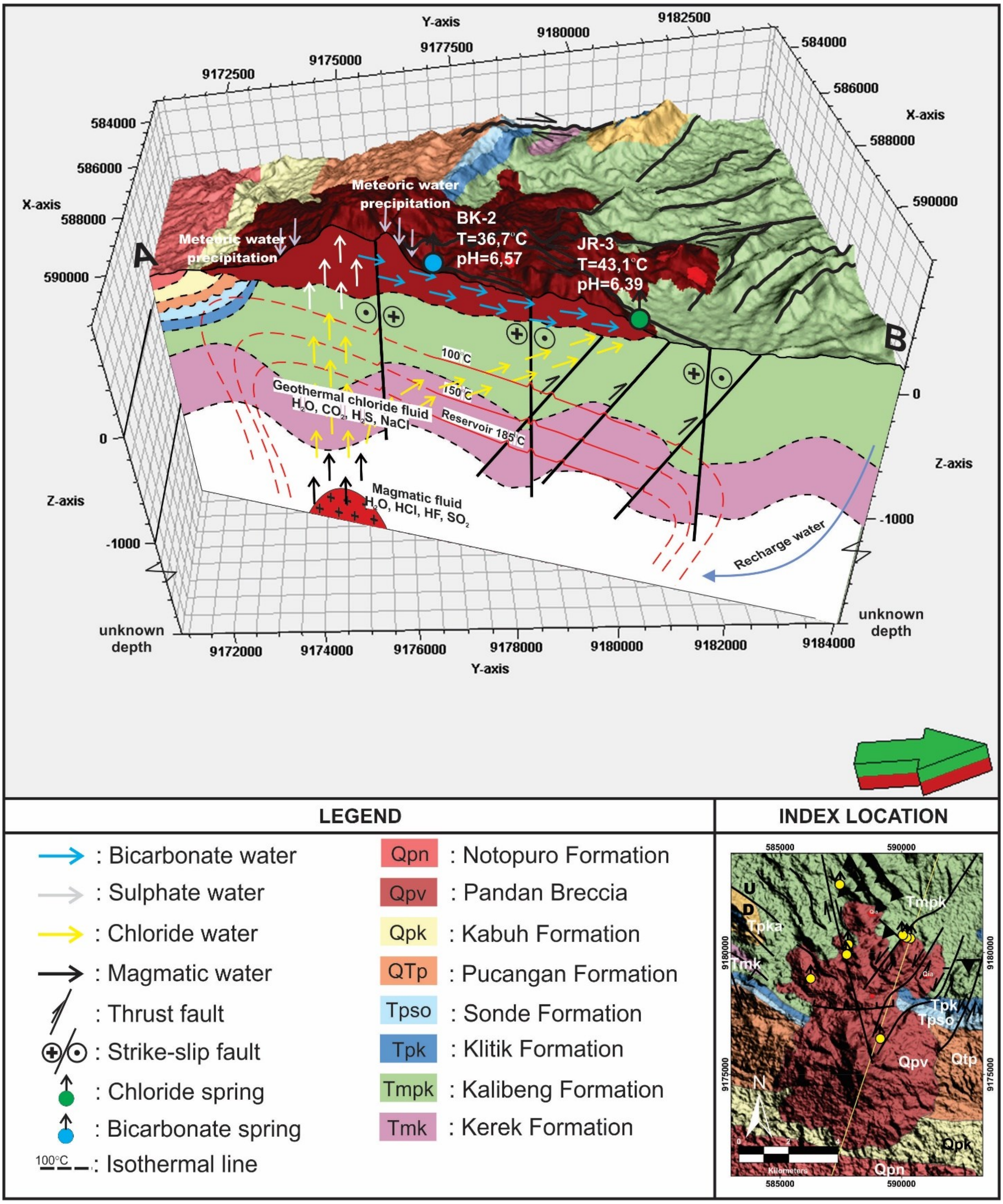

Figure 10: Mount Pandan geothermal conceptual model

4. CONCLUSION

The manifestations Mount Pandan has an unusual water type compared to other volcanoes in Indonesia due to the presence of sedimentary rock in the shallow depth. The 12 manifestations in Mount Pandan are outflow zone product which in the peripheral zone of the geothermal system. Banyukuning warm springs are bicarbonate water and Jari warm springs are chloride water. Beside the unusual of the water, Mount Pandan is located in the complex of geological structure, there are thrust fault, two major strike-slip fault, and normal fault. The emergence of geothermal manifestations on the surface due to fractures or weak zones that become fluid pathways to appear on the surface. The manifestations in Mount Pandan are controlled by E-W thrust fault which cut off by NW-SE dextral fault and NE-SW sinistral fault. JR-1, JR-2, JR-3, Tadahan (TD) and Banyukuning (BK) warm springs are controlled NE-SW fault and JR-4, JR-5 and Pragelan (PG) warm spring are controlled by NW-SE dextral fault. Based on the geological data and chemical analyses of the fluids we can conclude that the upflow zone is predicted on the south of BK manifestations with reservoir temperature approximately around 185°C. The reservoir rocks in the Mount Pandan geothermal system are sedimentary, based on geochemical analysis and subsurface electromagnetic data.

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